US008559692B2

(12) **United States Patent**
Reboni et al.

(10) **Patent No.: US 8,559,692 B2**
(45) **Date of Patent: *Oct. 15, 2013**

(54) **METHOD FOR CORRECTION OF DIGITAL IMAGES**

(71) Applicant: **Zakrytoe akcionernoe obshchestvo "Impul's"**, Sankt-Petersburg (RU)

(72) Inventors: **Vol'demar Osval'dovich Reboni**, Sankt-Petersburg (RU); **Anatoly Ivanovich Mazurov**, Sankt-Petersburg (RU); **Yan Sergeevich Leyferkus**, Sankt-Petersburg (RU)

(73) Assignee: **Zakrytoe akcionernoe obshchestvo "Impul's"**, Sankt-Petersburg (RU)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **13/853,822**

(22) Filed: **Mar. 29, 2013**

(65) **Prior Publication Data**

US 2013/0223717 A1 Aug. 29, 2013

Related U.S. Application Data

(63) Continuation-in-part of application No. 13/239,807, filed on Sep. 22, 2011, now Pat. No. 8,417,048, which is a continuation of application No. PCT/RU2010/000612, filed on Oct. 21, 2010.

(30) **Foreign Application Priority Data**

Jun. 8, 2010 (RU) 2010123733

(51) **Int. Cl.**
G06K 9/00 (2006.01)
G06K 9/40 (2006.01)

(52) **U.S. Cl.**
USPC **382/132**; 382/254

(58) **Field of Classification Search**
USPC 382/254, 266, 274, 275, 240, 132
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

7,149,358	B2	12/2006	Langan
2003/0161519	A1	8/2003	Vuylsteke
2005/0141780	A1	6/2005	Takahashi
2008/0205785	A1	8/2008	Geiger et al.

FOREIGN PATENT DOCUMENTS

EP	1345170	A1	9/2003
EP	2120040	A1	11/2009

OTHER PUBLICATIONS

Sorenson, J.N. et al., "Scattered Radiation in Chest Radiography", Progress in Medical Imaging, 1988 pp. 159-184.

Maher K.P. et al., "Computerized Scatter Correction in Diagnostic Radiology", Contemporary Physics, 1997, vol. 38, No. 2, pp. 131-148.

Love L. et al., "Scattered Estimation for a Digital Radiographic System Using Convolution Filtering", Medical Physics, 1987, vol. 14, No. 2, pp. 178-185.

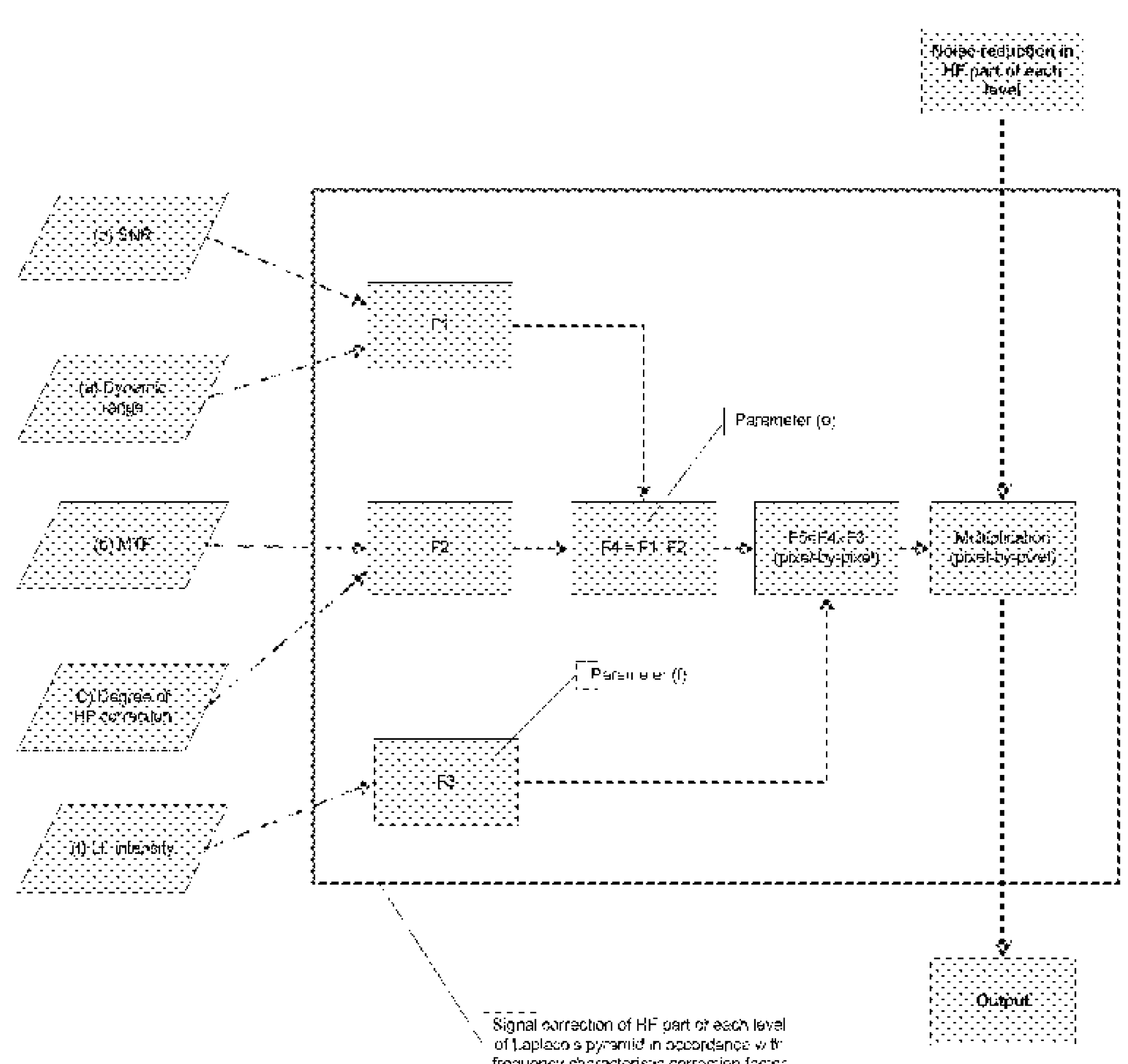
International Search Report dated Mar. 15, 2011 from corresponding International Patent Application No. PCT/RU2010/000612 filed Oct. 21, 2010.

Primary Examiner — Yon Couso
(74) *Attorney, Agent, or Firm* — Patentbar International, P.C.

(57) **ABSTRACT**

The method for correction of a digital image acquired with the use of electromagnetic radiation including X-rays, converted into electric signal and sent to digital imaging device, is provided, comprising pyramidal decomposition of a digital image into detailed and approximation images, removal of scattered radiation in approximation part of the images, contrast enhancement in detailed part of the images, merging of processed detailed and approximation images, the following reconstruction and generation of the final image. The results of the embodiment of this method comprise removal (reduction) of the scattered radiation component, noise reduction, correction of the dynamic range of the output image in accordance with the dynamic range of the output device, and scaling of the dynamic range of the output image in accordance with the dynamic range of the original image.

6 Claims, 6 Drawing Sheets



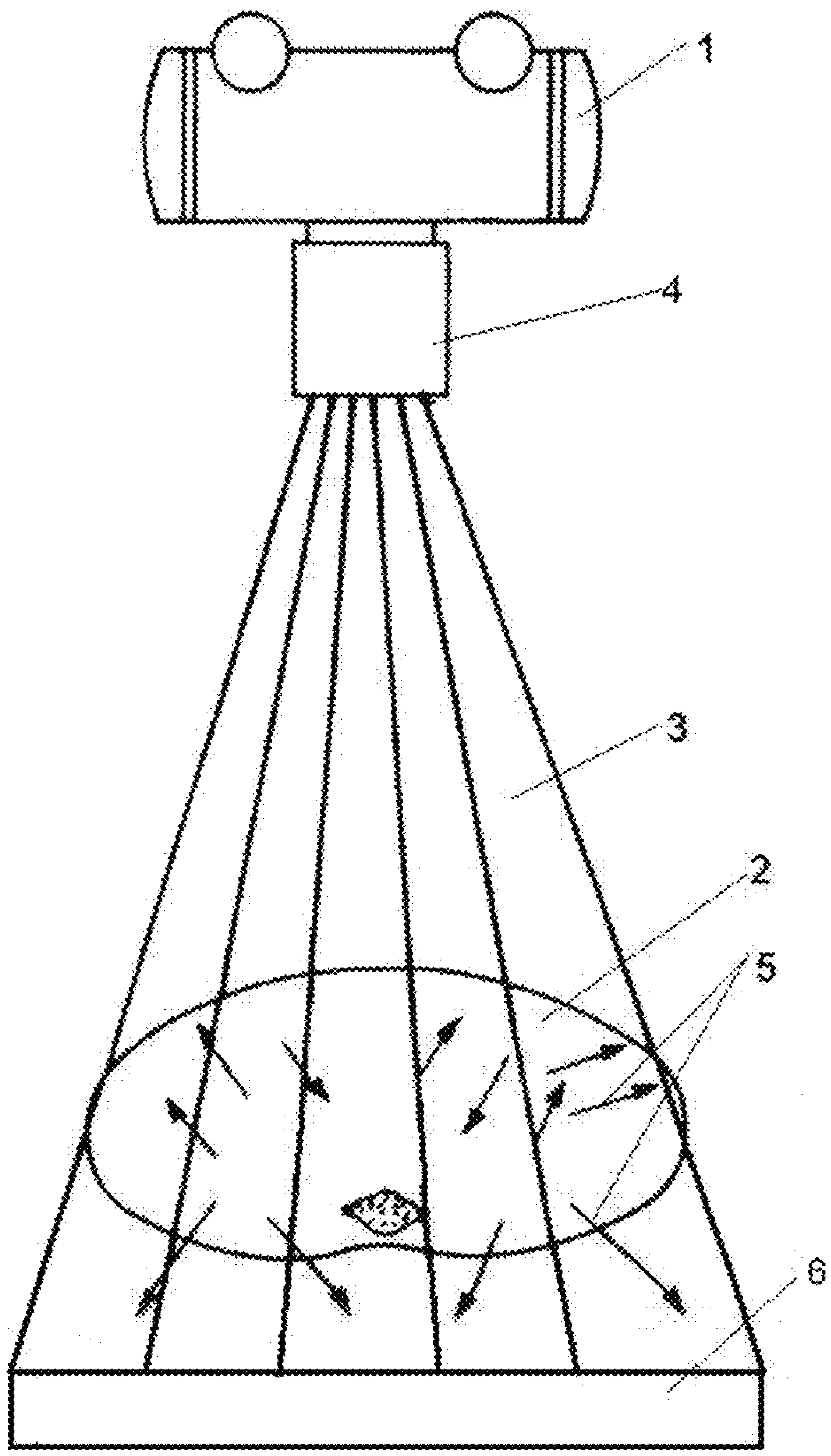


Fig. 1.

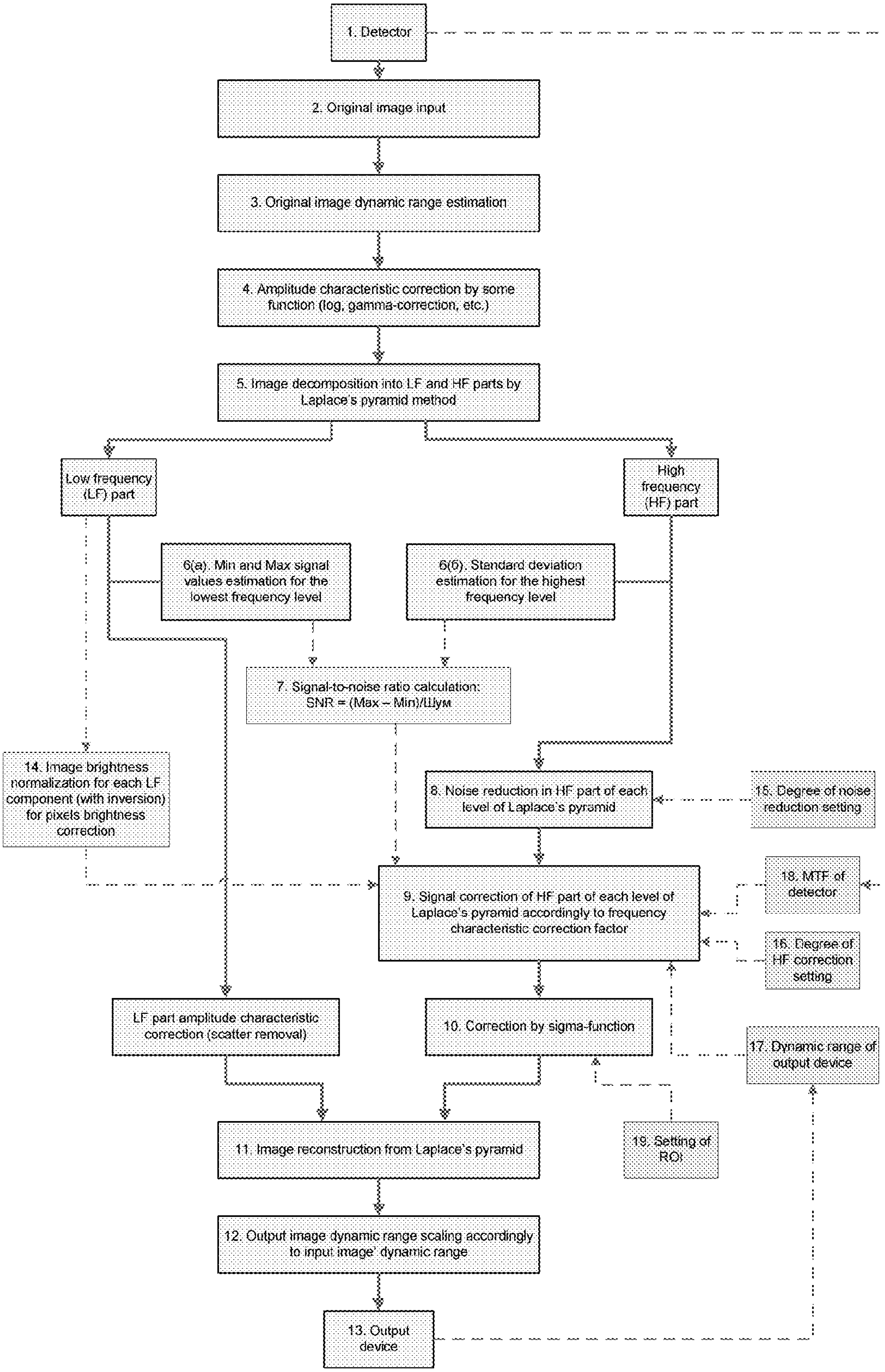
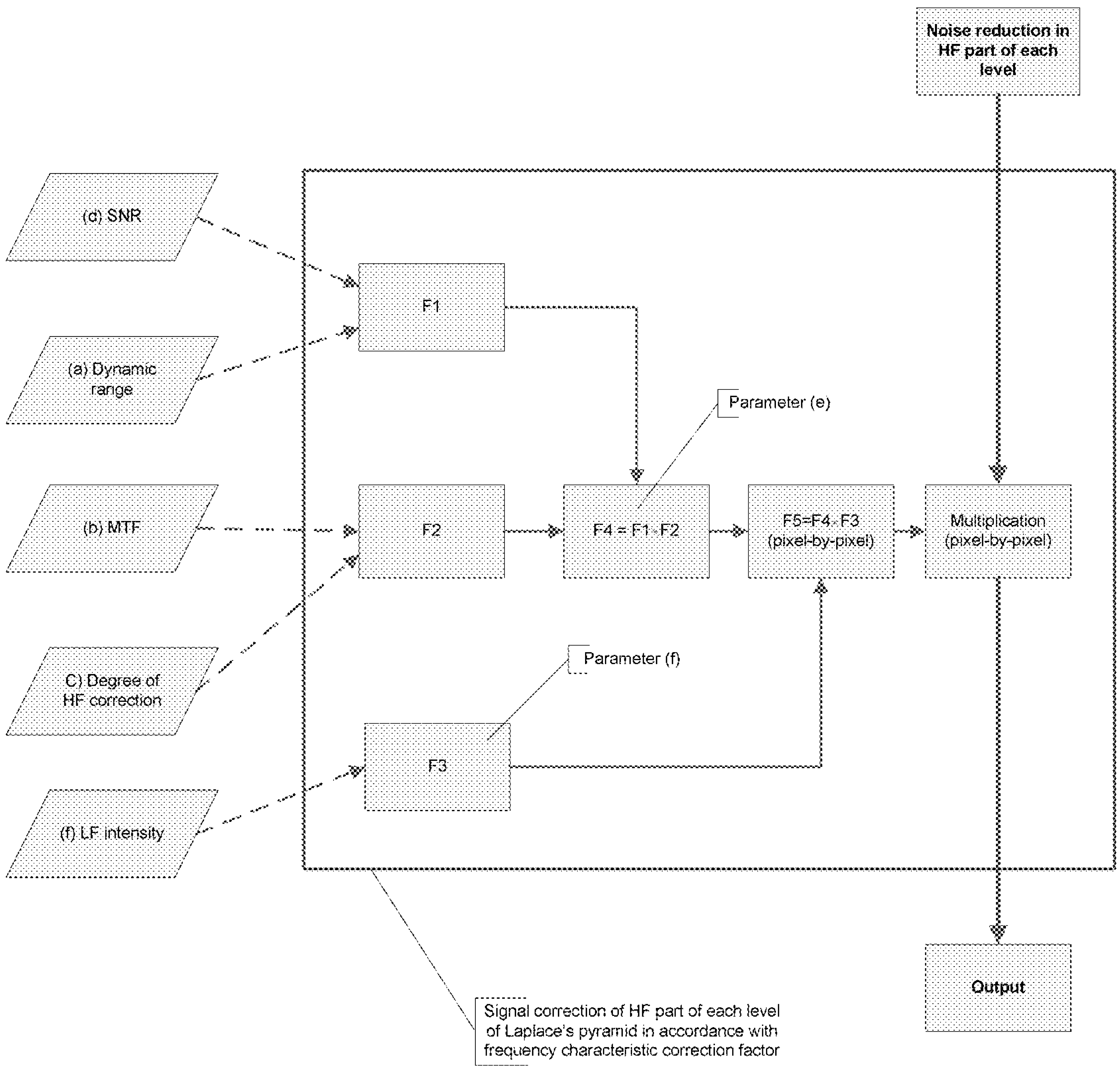

1. Detector
2. Original image input
3. Original image dynamic range estimation
4. Amplitude characteristic correction by some function (log, gamma-correction, etc.)
5. Image decomposition into LF and HF parts by Laplace's pyramid method
Low frequency (LF) part
High frequency (HF) part
6(a). Min and Max signal values estimation for the lowest frequency level
6(б). Standard deviation estimation for the highest frequency level
7. Signal-to-noise ratio calculation: SNR = (Max – Min)/Шум
14. Image brightness normalization for each LF component (with inversion) for pixels brightness correction
8. Noise reduction in HF part of each level of Laplace's pyramid
15. Degree of noise reduction setting
9. Signal correction of HF part of each level of Laplace's pyramid accordingly to frequency characteristic correction factor
18. MTF of detector
16. Degree of HF correction setting
LF part amplitude characteristic correction (scatter removal)
10. Correction by sigma-function
17. Dynamic range of output device
19. Setting of ROI
11. Image reconstruction from Laplace's pyramid
12. Output image dynamic range scaling accordingly to input image' dynamic range
13. Output device

Fig. 2.



Noise reduction in HF part of each level
(d) SNR
(a) Dynamic range
(b) MTF
C) Degree of HF correction
(f) LF intensity
F1
F2
F3
Parameter (e)
Parameter (f)
F4 = F1·F2
F5=F4·F3 (pixel-by-pixel)
Multiplication (pixel-by-pixel)
Output
Signal correction of HF part of each level of Laplace's pyramid in accordance with frequency characteristic correction factor

Fig. 3.

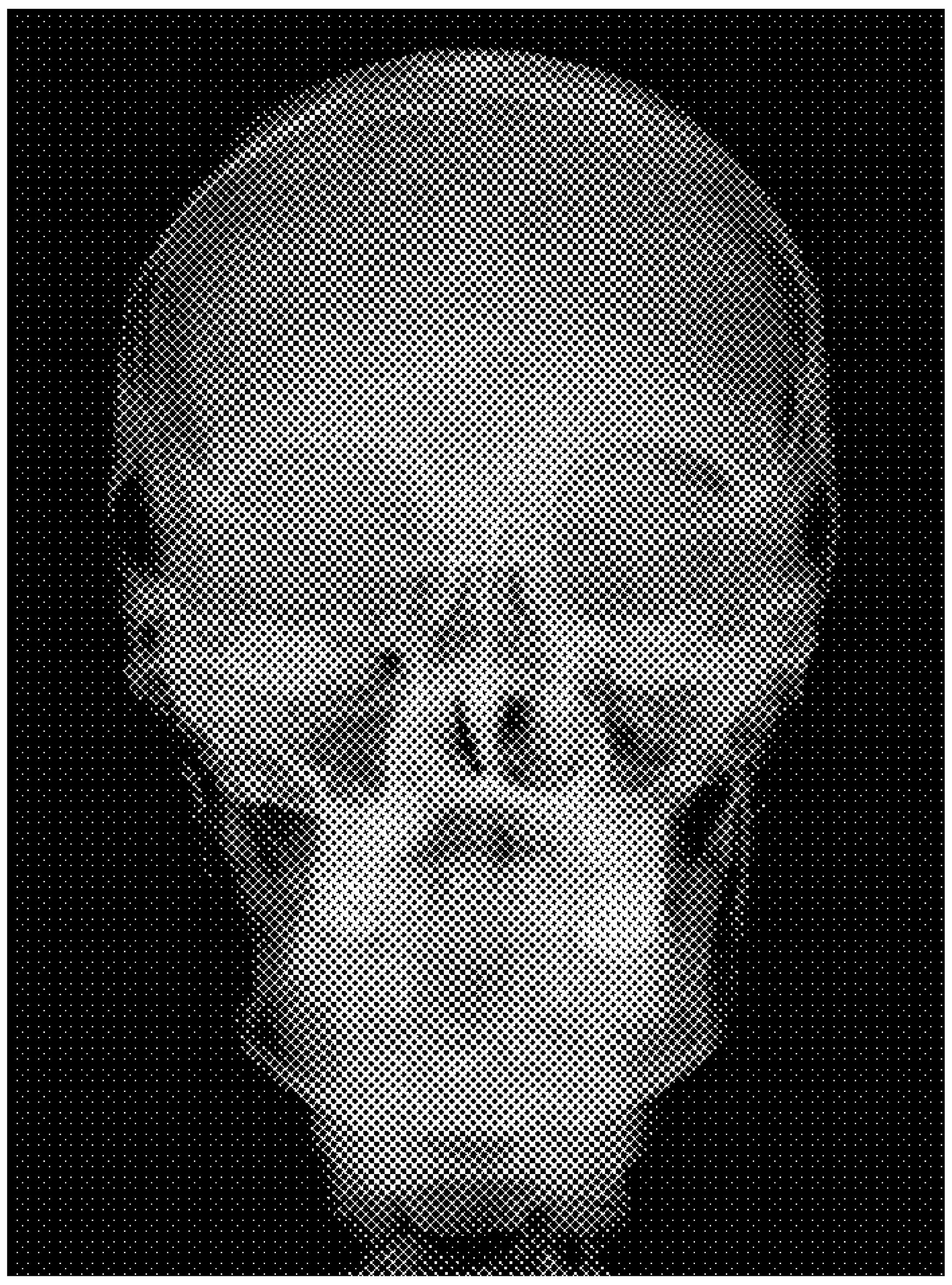


Fig. 4

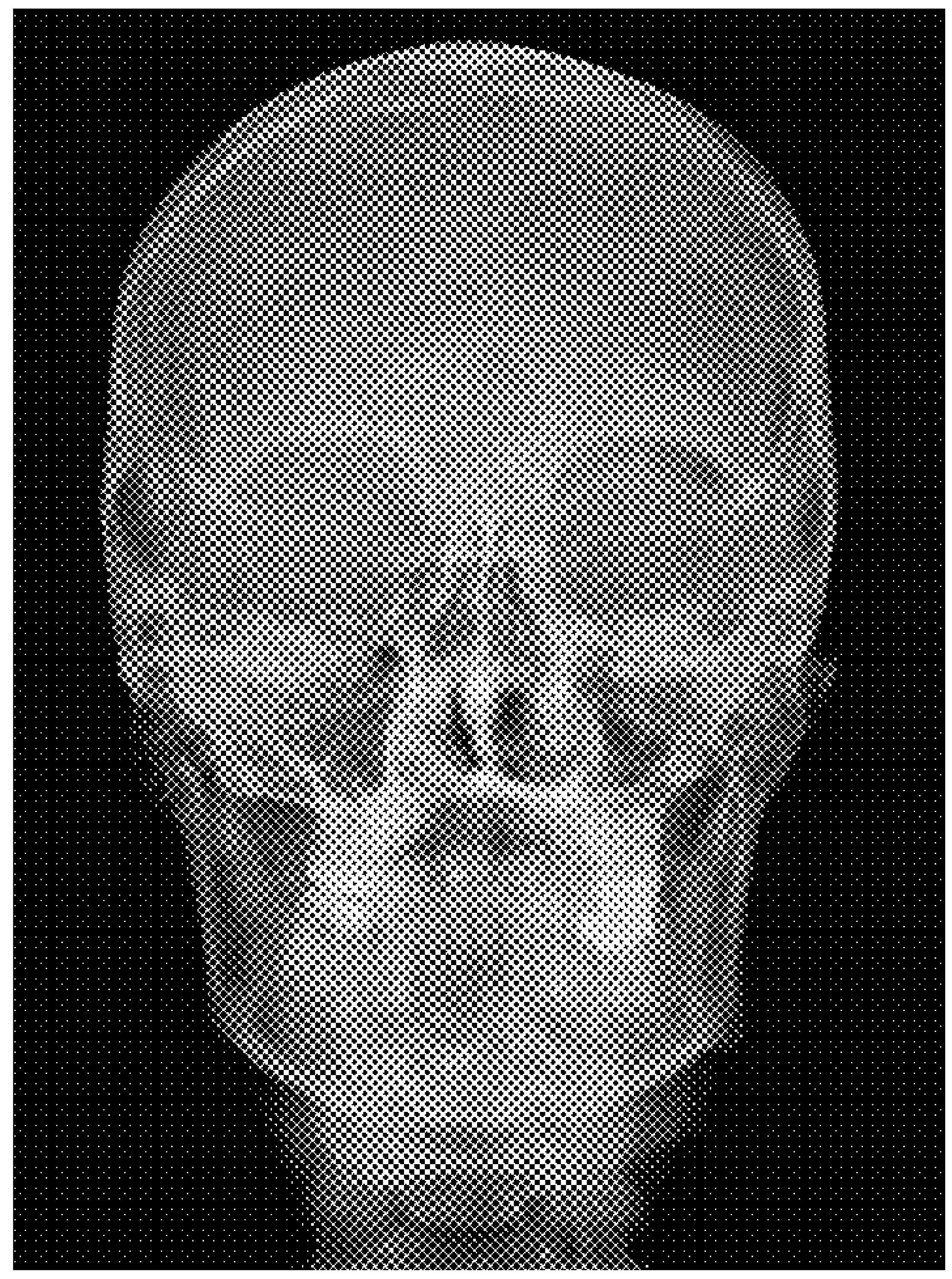


Fig. 5

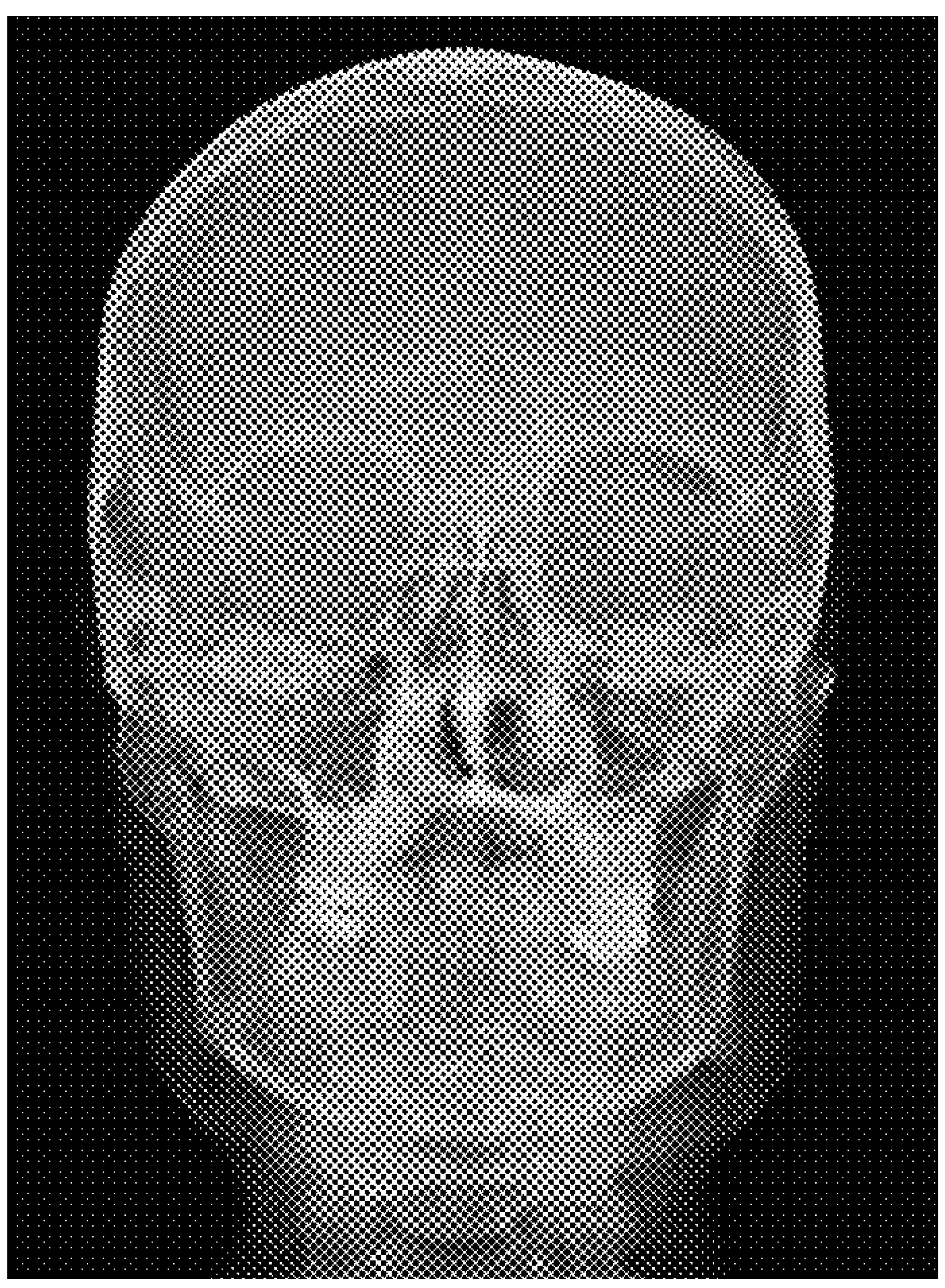


Fig. 6

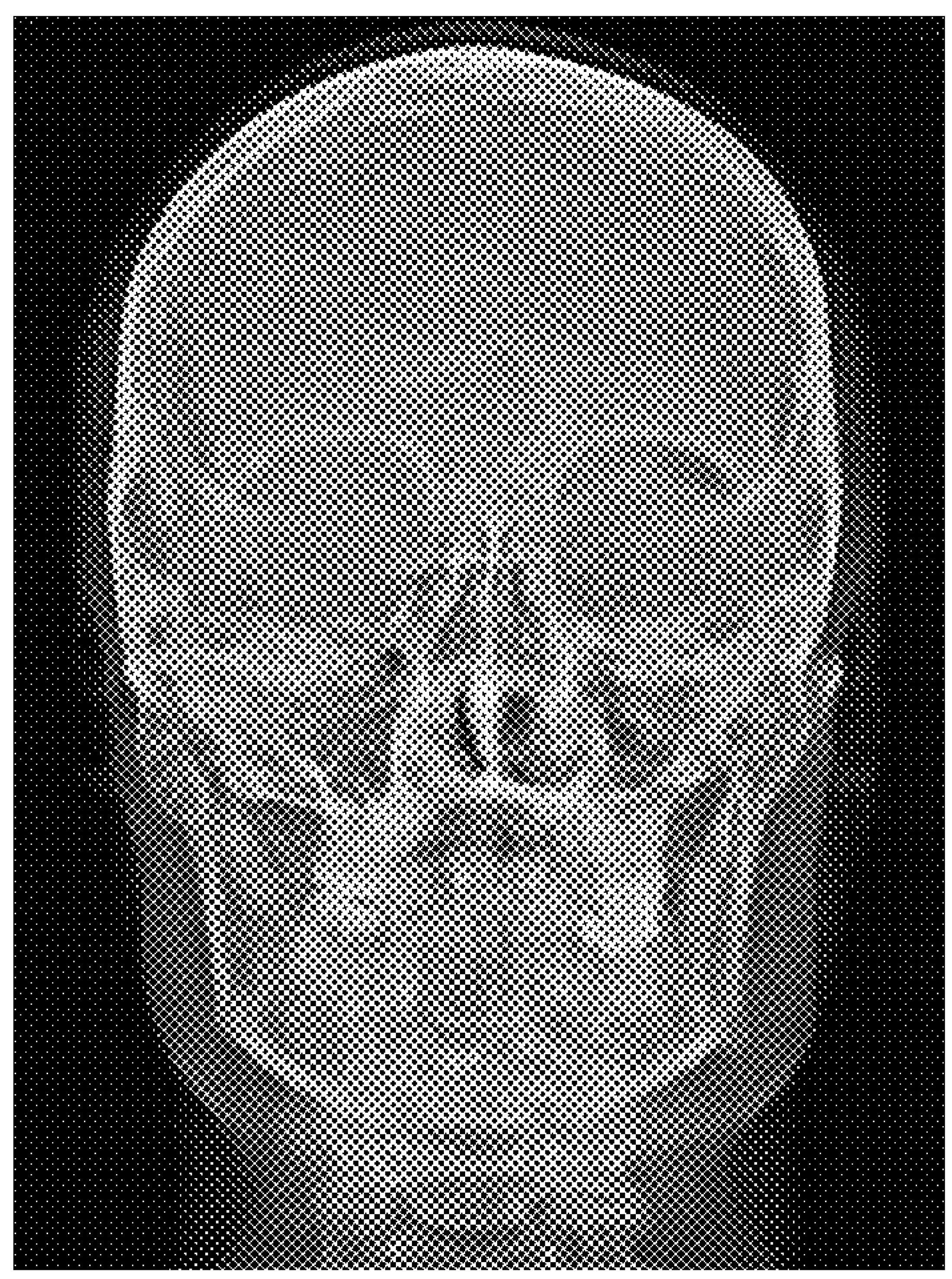


Fig. 7

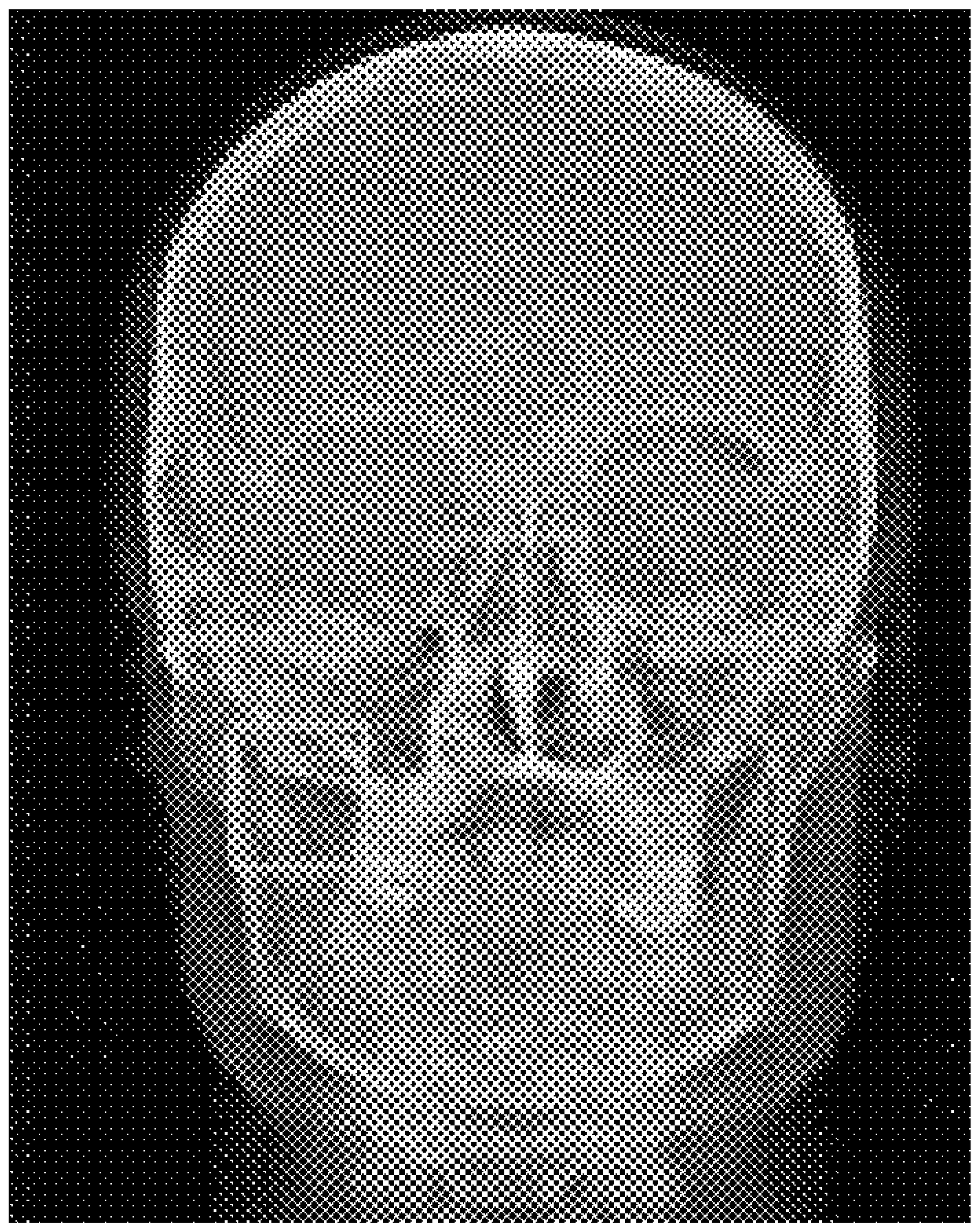


Fig. 8.

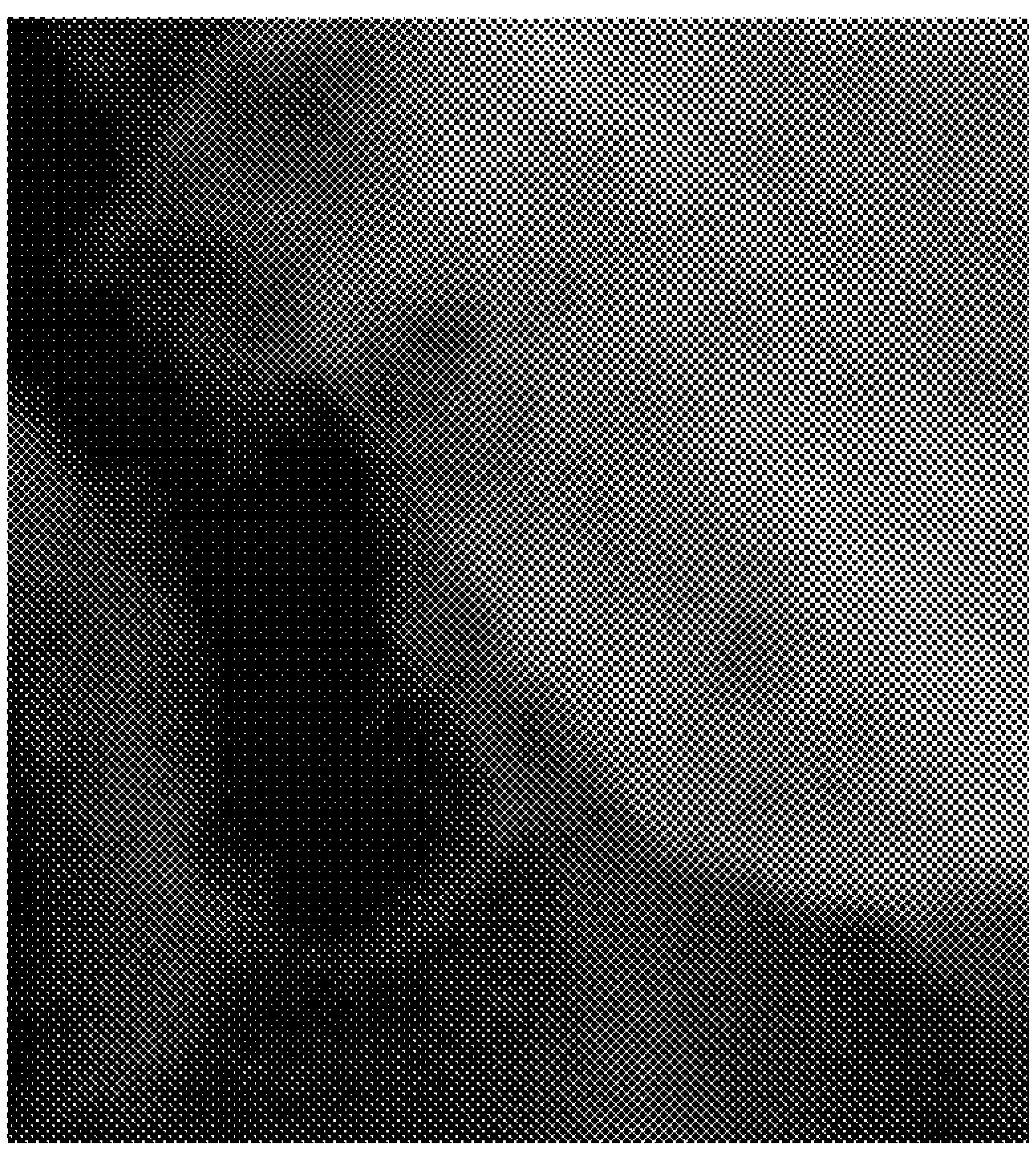


Fig. 9

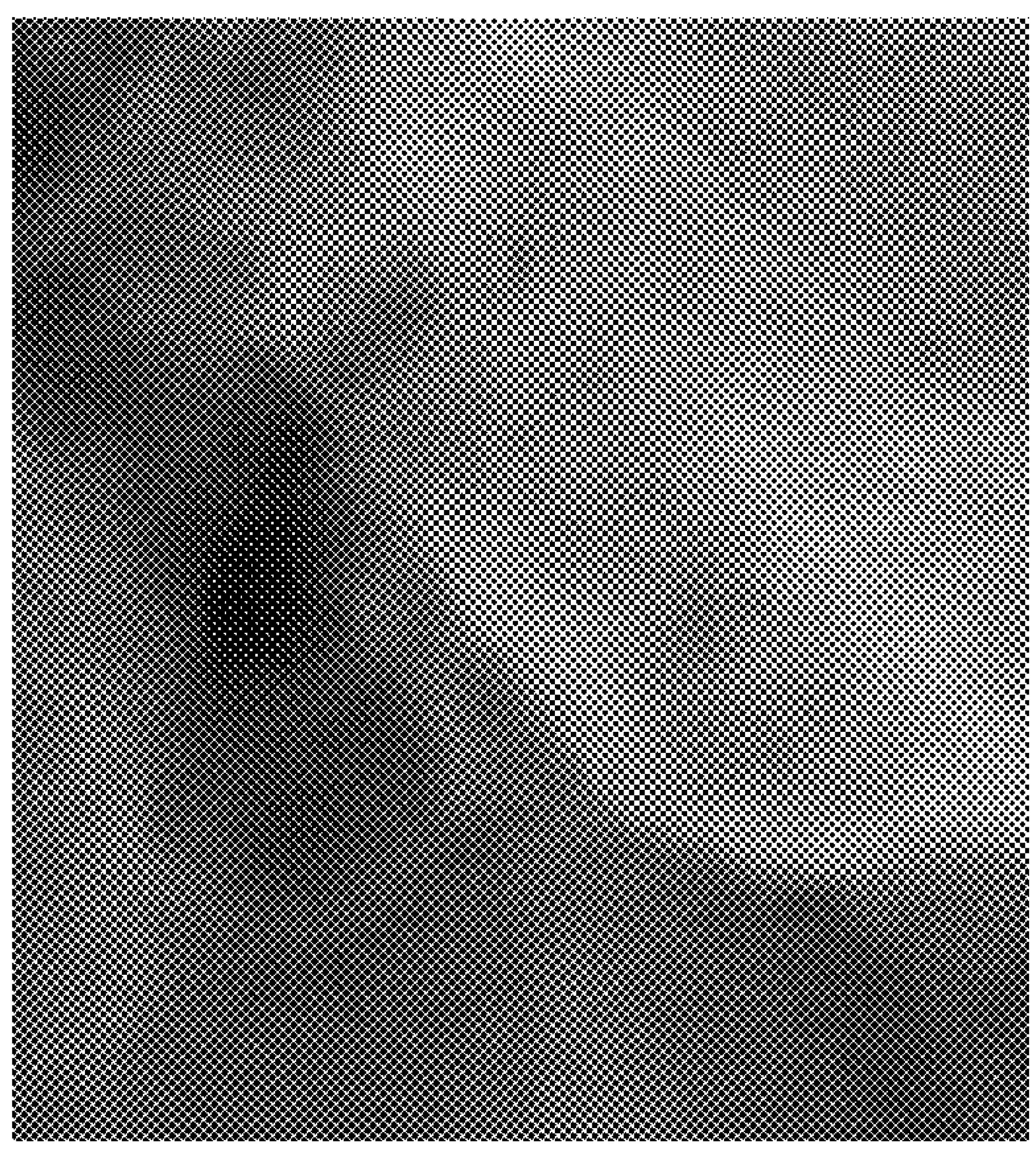


Fig. 10

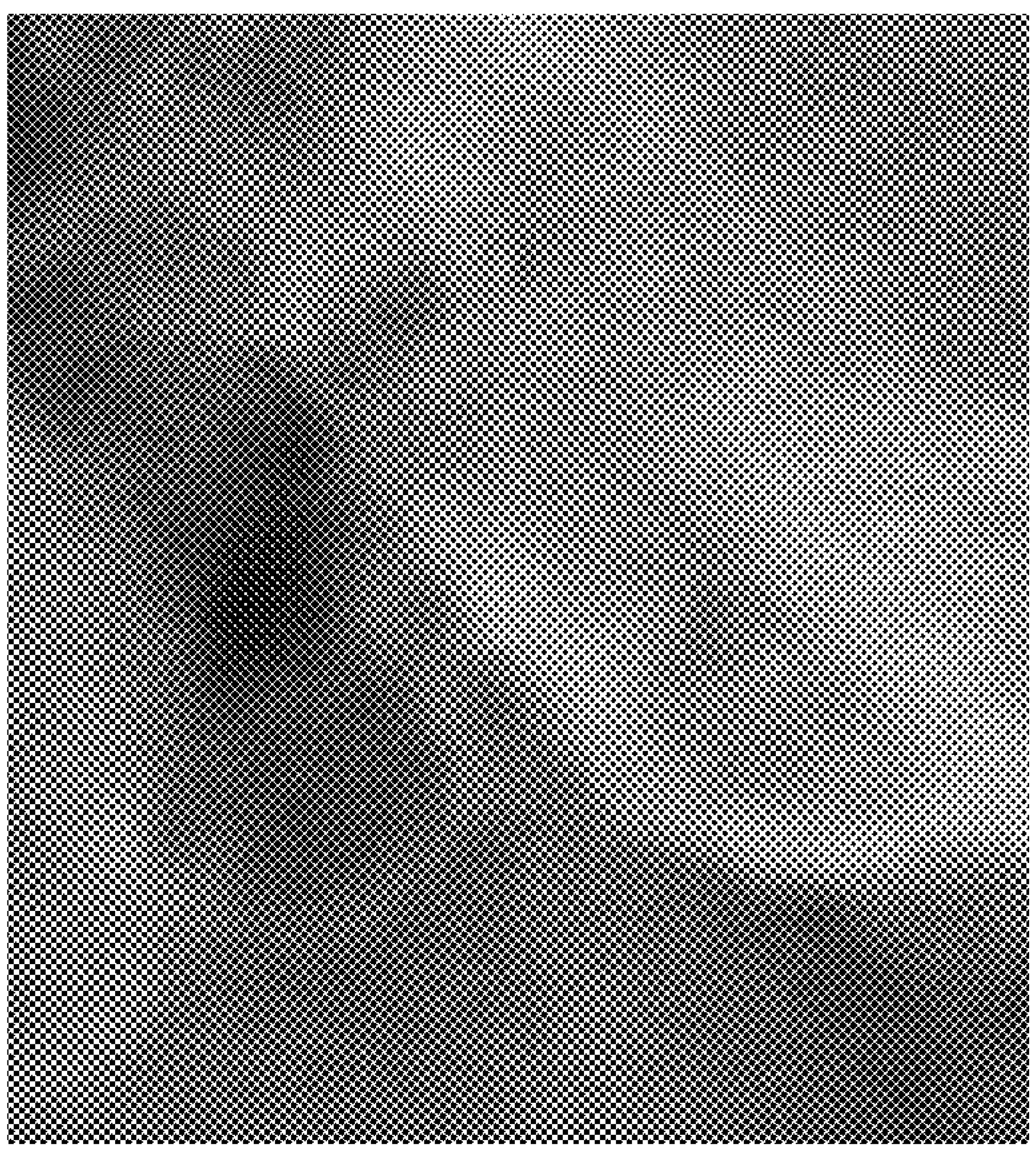


Fig. 11

Fig. 12

METHOD FOR CORRECTION OF DIGITAL IMAGES

RELATED APPLICATIONS

This application is a Continuation-in-Part of U.S. patent application Ser. No. 13/239,807, filed Sep. 22, 2011, which is a Continuation application of International Application PCT/RU2010/000612 filed on Oct. 21, 2010, which in turn claims priority to Russian application No. RU2010123733 filed on Jun. 8, 2010, all of which are incorporated herein by reference in their entirety.

FIELD OF THE INVENTION

This invention belongs to the field of digital image processing and can be used for the task of processing of digital images, acquired by means of use of high energy radiation, including the X-ray radiation.

BACKGROUND OF THE INVENTION

Irradiation of the object gives rise to scattered radiation, which has a strong effect on the detectability of details in the acquired images. Scattering leads to the reduction in contrast, densitometric imprecision and deterioration of image sharpness. Standard methods of treating the effects of scattered radiation usually directed towards reduction of the intensity of scattered radiation which reaches the image detector (Sorenson, J. A., and Niklason, L. T., 1988, Progress in Medical Imaging, edited by V. L. Newhouse (New York: Springer), pp. 159-184). In many instances implementation of such methods can lead to increase in the dose (by a factor of three or more) and in the noise of the acquired image.

Standard methods solve the problem of reducing the effects of scatter in primary image by means of anti-scatter grids, air gaps and beam collimation. These approaches reduce the scatter component of the total signal at the detector. However, they do not totally remove it, and they do not affect the veiling glare component directly. Also, the use of anti-scatter grids or air gaps leads to significant increase of the dose (patient exposure)(Sorenson, J. A., and Niklason, L. T., 1988, Progress in Medical Imaging, edited by V. L. Newhouse (New York: Springer), pp. 159-184).

Compensation of the scatter effects can be facilitated by use of computerized image processors connected to an image detector—such as in digital radiographic and fluoroscopic systems (Maher, K. P., and Malone, J. F., 1986, Contemp. Phys., 27, 533). Methods developed so far usually involve an estimation of scattered radiation field and its subtraction from the original image (Love. L. A., and Kruger, R. A., 1987, Medical Physics, 14, 178).

The method, most closely related to this claim, is the method of digital image correction (Patent No. EP2120040A1, published 18 Nov. 2009), acquired by means of electromagnetic radiation, including X-ray radiation, which was converted into electric signal and sent to digital imaging device, which includes pyramidal (Laplacian pyramid) decomposition of initial digital image into detailed (high-frequency band) images and approximation (low-frequency band) images, removal of scattered radiation in the approximating part of the images, enhancing the contrast in the detailed part of the images, re-composition of processed approximation and detailed images, which followed by reconstruction and generation of the resulting image.

SUMMARY OF THE INVENTION

The drawback of the abovementioned method is that it doesn't provide the possibility of correction of amplitude and frequency properties of the image, noise reduction, removal of effects of scatter and correction of dynamic range of the image in accordance with dynamic range of the output device.

Technical result of the invention is the possibility of correction of amplitude and frequency characteristics of an image, noise reduction, removal of scatter effects and correction of the dynamic range of an image in accordance with the dynamic range of an output device.

This technical result in the method for correction of digital image, acquired by means of electromagnetic radiation, including X-ray radiation, and converted into electric signal and sent to a digital imaging device, involving pyramidal decomposition of the original digital image into detalization and approximation images, scatter removal in approximation images, contrast enhancement of detalization images, re-composition of processed detailed and approximation images and concurrent reconstruction and output image, is achieved by the following means: before the aforementioned operation of image decomposition the dynamic range of the image is determined and amplitude characteristic is adjusted; after the aforementioned operation of image decomposition signal-to-noise ratio is determined, noise reduction is performed in detailed images which are also adjusted in accordance with frequency characteristic adjustment coefficient, which is determined by dynamic range of the output device, MTF of original imaging device, predetermined (pre-set) degree of the correction of detailed images and signal-to-noise ratio, determined earlier. This is followed by adjustment of detailed images in accordance with pre-set adjustment coefficient and intensity of approximation images, correction of edge artifacts in detailed images with the use of information about minimum and maximum values in each level of detailed images, and after performing said reconstruction of the image the dynamic range of the output image is scaled accordingly to the dynamic range of the original digital image and the output image is then sent to the output device.

Decomposition of the original digital image can be performed, for example, by Laplace's method or wavelet transform method.

Signal-to-noise ratio can be determined as a ratio of difference between maximum and minimum signal in approximation images and noise value for detailed images.

Edge artifact correction is performed by means of sigma function, parameters of which depend on maximum and minimum values in the region of interest of detailed images and MTF value of the digital imaging device, used in determination of frequency characteristic correction coefficient.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1-12**: example of embodiment of the invention, which illustrates the principles behind the claimed invention, and demonstrates the possibility of technical realization and the achievement of claimed technical result.

FIG. **1**: Schematic diagram of X-ray image acquisition;

FIG. **2**: The complete scheme of the algorithm;

FIG. **3**: Scheme of the subroutine of correction of high-frequency part of each level of Laplace's pyramid;

FIG. **4**: The original digital image;

FIG. **5-7**: Images processed according to the method of the claim;

FIG. **8**: The position of the fragment on the whole image;

FIG. **9-12**: Fragment of the image, processed according to the claimed method.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

As shown in the FIG. **1**, X-ray tube **1** with collimator **4** emits the X-ray beam **3** which passes through the object **2** under investigation. The X-ray radiation is detected by the digital imaging device (detector) **6** from which it is sent to the display.

After that the method is performed in the following sequence of operations (FIG. **2**) which is described below.

The MTF of detector **6** is determined;

The image to be processed is input ("the original image") (pos. **4**, FIG. **2**);

The dynamic range (min-max) of the original image is determined (pos. **3** in FIG. **2**);

The amplitude characteristic of the image is adjusted (optional) (pos. **4** in FIG. **2**). Logarithmic method may be used for the adjustment of the amplitude characteristic of the image. The signal of the original image has the following value:

$$U=U_0 \cdot e^{-\mu t}$$

where U—"original" signal, U_0—radiation dose (exposure), μ—X-ray absorption factor for the object material, t—thickness of the object. After logarithmization of this equation becomes:

$$1nU=\mu \times t+1nU_0$$

Therefore, the output signal becomes proportional to total value of the X-ray absorbtion factor.

The image is decomposed according to the Laplace pyramid method (pos. **5** in FIG. **2**), where the image is divided into the low frequency (LF) (approximating) part and high frequency (HF) (detailed) part. These parts are concurrently divided into LF and HF parts and so on.

The signal-to-noise ratio (SNR) is determined as follows (FIG. **2**):

the minimum (Min) and maximum (Max) value of the signal is determined for the lowest frequency level of the Laplace's pyramid (Pos. **6**(*a*) in FIG. **2**);

the standard deviation is determined for the highest frequency level of the Laplace's pyramid (which is equivalent to measuring the Noise in this level) (Pos. **6**(*b*) in FIG. **2**);

the SNR (signal-to-noise ratio) (pos. **7** in FIG. **2**) is calculated in accordance with the following equation:

$$SNR = \frac{\text{Min} - \text{Max}}{\text{Noise}}.$$

The noise reduction is performed in the following way: in each level of the Laplace pyramid high frequency part is processed with the separate noise reduction algorithm (Pos. **8** in FIG. **2**), which can be based on the wavelet transform, non-local mean, bilateral transform methods, etc. and their combination. The degree of the noise reduction can be set in advance within the range 0%-100%.

Subroutine of determination of the frequency characteristic correction coefficient is controlled by the following parameters (Pos. **9** in FIGS. **2** and **3**):

a) The dynamic range (pos. **17** in FIG. **2**, parameter (a) in FIG. **3**) to which the original dynamic range of the image is limited in accordance with the dynamic range of the output device (film printer, computer monitor, etc.);

b) The MTF of the detector (pos. **18** in FIG. **2**, parameter (b) in FIG. **3**), with which the original image was acquired;

c) The degree of adjustment of high frequencies (HF gain) (set in % increase/reduction) (Pos. **16** in FIG. **2**, parameter (c) in FIG. **3**);

d) The value of SNR, determined previously (Pos. **7** in FIG. **2**, parameter (d) in FIG. **3**).

The HF images in each level of the pyramid are adjusted by means of the frequency characteristic correction coefficient (fccc), obtained at the stage of the amplitude characteristic correction by a function (Pos. **9** in FIG. **2**). This correction is controlled by two parameters:

e) The correction coefficient (parameter F**4** in FIG. **3**), which was obtained during the determination of the dynamic range of the original image (Pos. **17** in FIG. **2**);

f) The brightness of the LF part of the image in the same level of the pyramid (HF gain is inversely proportional to the brightness through some function or linear dependence);

The process of frequency characteristic correction is shown in detail in FIG. **3**. Parameters (a-d) ((a)—dynamic range, (b)—MTF, (c)—degree of HF correction, (d)—signal-to-noise ratio (SNR)) are transformed as follows: parameters (a-d) are transformed by certain functions, whose parameters are dependent on the level of Laplace's pyramid (see FIG. **3**) (parameters (a) and (d) are transformed by the function F**1**, parameters (b) and (c)—by the function F**2**) and then the result of these transformations is itself transformed by the function F**4**, which in this case is simply a multiplication operation. The final result is the corection coefficient, i.e. fccc.

This correction is controlled by two parameters. The first parameter (parameter (e) in FIG. **3**) is frequency characteristic correction coefficient, fccc, which is common for all the pixels in the input of this subroutine, and second parameter (parameter (f) in FIG. **3**) is determined by pixel brightness in LF component and is specific for each pixel. The value of each pixel in the input of the subroutine is multiplied by the product of the correction coefficient fccc and parameter (f), which is specific for each pixel, where parameter (f) is inversly proportional to the brightness of a pixel, accordingly to some function or linear dependence.

In short the process of correction of HF component can be described as follows: Entrance parameters of the subroutine are transformed by some functions (F**1**, F**2**, F**3** with parameters, dependent on the level of Laplace's pyramid), then these parameters are also transformed by the function F**4** (which in this case is simply a multiplication) into the correction coefficient, by which the data of HF parts of the image at the input of this subroutine is transformed. Input parameters of the subroutine of correction of HF component are as follows:

SNR—signal-to-noise ratio (pos. **7** in FIG. **2**);

Dynamic range of the output device (pos. **17** in FIG. **2**) (determined by a method, known to those skilled in the art);

MTF—modulation transfer function (pos. **18** in FIG. **2**) (determined by a method, known to those skilled in the art);

Degree of correction (pos. **16** in FIG. **2**) which is selected by the operator accordingly to an imaging task (depending on modality, anatomical region of interest and patient size);

Brightness of LF part (pos. **14** in FIG. **2**), correction coefficient (for each pixel in the image) is formed accordingly to brightness of LF components (higher brightness—lower correction coefficient).

To avoid the edge over-enhancement of image structures (edge artifacts) the minimum and the maximum values are determined in the region of interest (ROI) of each HF part, and based on them the parameters of the sigma function, which is used for the processing of the HF parts of the image, are determined (Pos. **10** in FIG. **2**). The region of interest in the image can be set by different methods—it can cover all of the image area, zones of the exposure meter, as an ellipse with parameters (size, position, orientation etc.), or automatically by an specialized algorythm with borders along edges of certain parts of patients anatomy (bodyparts or organs).

The reverse reconstruction of the image from Laplace's pyramid is performed (Pos. **12** in FIG. **2**).

The dynamic range of the resulting image is scaled accordingly to the dynamic range of the original image (Pos. **13** in FIG. **2**).

The processed image is sent to the output device (Pos. **14** in FIG. **2**).

The possibility of achieving the technical result demonstrated in FIGS. **4-12**. In FIG. **4** shown the original digital image, part of bone structure is not visible (dark areas). In the image with light processing (FIG. **5**) it is possible to see almost all bone structure. In the image with medium processing (FIG. **6**) it is possible to see all of the bone structure and part of the soft tissue. In the image with heavy processing (FIG. **7**) it is possible to see all of the bone structure and practically all of the soft tissue.

The FIG. **8** shows the position of the fragment on the whole image.

On the fragment of the whole image (FIG. **9**) it is possible to see the noise and the lack of detalization.

On the fragment of the image with light processing (FIG. **10**) the noise is removed and detalization is enhanced.

On the fragment of the image with medium (normal) processing (FIG. **11**) the detalization is brought to the normal level.

On the fragment of the image with heavy processing (FIG. **12**) all of the bone structure is visible in detail with acceptable noise level.

The examples of image processing with use of the method of the claim are demonstrated in FIGS. **4-12**, which show the effect of two main parameters of the filter. The first parameter—dynamic range of the output image in arbitrary units, which are related in their sense to the value Smax/Smin, where Smax—maximum value of the signal in the image, Smin—minimum value. The range of values is 16-2048.

The second parameter is the degree of noise reduction in percent. The range of values is 0-100%. 0%—there is no noise reduction; 100%—all noise is removed.

Parameters for the images in the Figures are as follows:

1. Light processing: dynamic range of the output image—256, degree of noise reduction—30%;
2. Normal processing: dynamic range of the output image—64, degree of noise reduction—60%;
3. Heavy processing: dynamic range of the output image—32, degree of noise reduction—90%.

INDUSTRIAL APPLICABILITY

Thus the technical result of the invention is achieved—correction of amplitude and frequency characteristics of the image, noise reduction, reduction of the effects of the scattered radiation and correction of the dynamic range of the image in accordance with the dynamic range of the prospective output device.

What is claimed is:

1. A method of correcting a digital image obtained using electromagnetic radiation, including X-rays, converted into an electric signal, and transmitted to a digital imaging device, comprising:

pyramidal decomposition of the digital image into detailed images and approximation images;

removal of scattered radiation in the approximation images to produce processed approximation images;

contrast enhancement of the detailed images to produce processed detailed images;

combining the processed detailed images and the processed approximation images; and

reconstruction and generation of a final image;

and further comprising:

before the decomposition,

determining a dynamic range of the digital image and correcting amplitude characteristics of the digital image;

after the decomposition,

determining a signal-to-noise ratio,

noise reduction in the detailed images,

correcting the detailed images using a frequency characteristic correction coefficient determined by

a dynamic range of an output device,

a modulation transfer function of a digital imaging device forming the digital image,

a set degree of correction of the detailed images, and

the signal-to-noise ratio;

correcting the detailed images using a correction coefficient and using a brightness of approximation images, and

correcting edge artifacts in the detailed images using minimum and maximum values for each level of the detailed images; and

after the reconstruction,

scaling a dynamic range of the final image using the dynamic range of the digital image, and

transmitting the final image to the output device.

2. The method of claim **1**, wherein the decomposition of the digital image is performed by the Laplacian pyramid method.

3. The method of claim **1**, wherein the decomposition of the digital image is performed by the wavelet transform method.

4. The method of claim **1**, wherein the signal-to-noise ratio is determined using a ratio of the difference between a maximum and a minimum value of a signal in the approximation images to a noise value for the detailed images.

5. The method of claim **1**, wherein the correction of edge artifacts in the detailed images is performed

by using a sigma function,

wherein the parameters of the sigma function are determined using minimum and maximum values of the detailed images; and

by using the modulation transfer function of the digital imaging device to determine the frequency characteristic correction coefficient.

6. The method of claim **1**, wherein the correction of edge artifacts in the detailed images is performed

by using a sigma function,

wherein the parameters of the sigma function are determined using minimum and maximum values of the detailed images within a region of interest; and

by using the modulation transfer function of the digital imaging device to determine the frequency characteristic correction coefficient.

* * * * *